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Cortical reorganization processes in meditation naïve participants induced by 7 weeks focused attention meditation training

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ABSTRACT

Background: Based on the evidence that meditation is associated with numerous beneficial effects on well-being and reduced stress-related symptoms, mindfulness-based techniques were increasingly implemented into psychotherapeutic programs. However, different meditation styles and the cross-sectional nature of most previous analyses resulted in a great variety of morphometric findings. The present study aims to elucidate cortical reorganization processes and altered axonal integrity caused by short-term meditation training, and benefits from solely using focused attention meditation (FAM).
Methods: 3 T MRI, including T1-MPRAGE and diffusion-weighted sequences, was performed in 27 healthy, meditation naïve participants (age: 43 ± 12.4 years) pre and post FAM meditation training (duration: 7.3 ± 0.4 weeks). Voxel-based morphometry was applied to assess brain changes in gray and white matter. Questionnaires were filled out by the individuals at both time-points to evaluate quality of life and self-awareness deficits.
Results: The major findings comprised (i) gray matter increases in the insula, the caudate nucleus and frontal cortices, (ii) decreases in extended parietotemporal regions, the right medial prefrontal cortex and the parahippocampal gyrus, as well as (iii) fractional anisotropy increases of the right hippocampus, the basal ganglia and adjacent regions. Regression analysis revealed an association of specific alterations with reduced levels of state anxiety.
Conclusions: FAM training induced a broad range of dynamic brain alterations even within few weeks of training. Interestingly, this cohort revealed more, and partially different patterns of structural gray matter change compared to prior studies. The broad impact on neuronal organization processes may reflect more general outcomes related to health and well-being.

1. Introduction

Over the past decades, meditation practices have been of particular interest for neuroscientists as they were associated with numerous positive effects on psychological well-being and quality of life. Convergent neuroscientific evidence has established the application of meditation techniques in reducing stress-related symptoms and improving clinical disorders such as anxiety and depression [1,2]. Even after a short period of training, meditation participants were shown to enhance various cognitive processes including emotional regulation, executive control and the ability to sustain attention [3,4]. To take advantage of these beneficial effects, mindfulness-based interventions were increasingly implemented into the treatment of altered physiological and psychological conditions [5,6]. Meditation is believed to impact structural connections of the brain that are neurobiological substrates of distributed regulatory processes underlying attention and emotion, that further promote improvements in well-being and behavioral aspects [7,8].

Numerous studies have begun to localize patterns of gray (GM) and white matter (WM) alterations shaped by meditation using voxel- and surface-based morphometry measures [9]. Further, morphological differences between meditators and non-meditators were linked to potential effects concerning the amount and duration of meditation practice [10,11]. The most consistently altered brain regions included

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areas of the fronto-insular, medial prefrontal cortex (mPFC) and hippocampal cortex, which are regions related to self-awareness, self-regulation and episodic memory [9]. However, the assessment of causal relationships between such changes and meditation has been limited due to the cross-sectional nature of most previous study designs. To establish putative causal effects on brain structure, several research groups have pioneered longitudinal analyses and suggested that meditation-related morphologic changes occur via mechanisms of structural plasticity [12–16]. Different meditation styles and the neuroimaging methods resulted in a great variety of morphometric results. For instance, longitudinal analyses showed increases in GM concentration within the left hippocampus [12] and cortical thickness in the right insula and the somatosensory cortex [14] after an 8-weeks mindfulness-based stress reduction training program. In a cohort of 14 patients with Parkinson's disease, who participated in an 8-week program of mindfulness-based intervention, increased GM density was detected in the bilateral caudate, parieto-temporal junction, left cuneus, left thalamus and left lingual gyrus [13]. Dodich et al. reported increased GM density in the right inferior frontal gyrus encompassing the anterior component of the executive control network after 4-week Sahaja Yoga meditation training [15], and Yang et al. found cortical thickness increases in the left posterior cingulate cortex (PCC)/ precuneus after 40 days of mindfulness meditation training in novices [16].

Meditation related brain alterations were reported for GM volume, cortical thickness and gyrification, but also for WM integrity. Diffusion-weighted imaging (DWI) is a non-invasive MRI technique used to assess the microstructural connectivity by quantifying the restriction of axonal water molecules termed fractional anisotropy (FA). Only few recent studies used DWI to assess WM changes in meditators [17–20]. Most of the training-related alterations in functional connectivity were found in regions that contribute to the default mode network (DMN), a set of anatomically defined subsections that are co-activated during passive task states and interconnected via direct and indirect anatomic projections [21]. While the anterior part of the DMN in known to be involved in regulation of emotional states, the posterior part plays a key role in self-referential processing. In consideration of the relative lack of longitudinal DWI studies, we believed that investigating the impact of meditation practices on axonal integrity alterations could further elucidate the dynamics of anatomical connectivity and mental health.

Moreover, it is noteworthy that plenty meditation techniques belonging to different traditions have been analyzed which vary enormously in aims, extent, difficulty and the demand of brain regions. In brief, the term meditation escribes a family-complex of different meditation styles, which can be grouped into two main categories according to their main cognitive processes: (i) focused attention (FAM), i.e. concentrating on a chosen object, breathing, image or words; and (ii) open monitoring meditation, i.e. paying non-evaluating awareness of ongoing experiences without judging, reacting or holding on [7]. Since attentive and non-reactive meditation techniques demand different cognitive domains, it is likely that these two meditation categories differ in eliciting brain activity, which may induce neuroplastic changes in various brain regions [22].

Although the convergent body of evidence suggests that alterations of neuronal networks are induced by meditation practices, the possibility of preexisting brain heterogeneities in cross-sectional study designs and different meditation traditions made it somewhat difficult to draw a cohesive picture of the relationship between meditation and brain morphology. To date, only few recent studies assessed causal effects of short-term meditation on brain architecture in meditation novices. The generalizability of previous findings has often been limited due to differences in individual characteristics, methodological approaches and the type of meditation. We aimed to fill this gap by using a prospective longitudinal study design in a larger cohort of meditation naïve participants. This particular study design specifically excludes the necessity of a control group, as the control for possible personal confounding permanent or preexisting factors on behavioral measures with and without FAM to another lies within each participant themselves. Further, this study benefits from specifically using FAM in meditation novices, whereas most prior meditation research depends on interventions and/or prior experience that engages a range of meditation styles making conclusions more difficult to draw and results more likely to be influenced by confounding factors. To the best of our knowledge, no previous comparable study had investigated causal effects of FAM on brain structure. The objective of our study was to elucidate cortical reorganization processes and altered axonal integrity in the brain parenchyma that are directly caused by short-term intensive FAM training for few weeks.

2. Materials and methods

2.1. Participants

Participants were independently living persons, who were newly recruited from the general population by advertisement of the local yoga school. None of the participants reported neurological, psychiatric or major medical disorders. All individuals were native German speakers and had normal or corrected-to-normal sight and hearing. Further inclusion-criteria were no prior meditation experience and completion of all 14 meditation classes. All participants underwent two 3 T MRI scans with a standardized protocol, one before and one after meditation training. The final study cohort consisted of 27 healthy individuals, 17 females and 10 males, who fulfilled the inclusion criteria and participated in the study. The mean age was 43 ± 12.4 years. The mean time between baseline and follow-up MRI scan was 7.3 ± 0.4 weeks.

Institutional review board and written participant consent were obtained (Ethics Committee of the Medical University of Innsbruck, Austria).

2.2. Meditation technique and training protocol

After baseline MRI, all enrolled participants were instructed in meditation practice based on a beginner's raja yoga technique. The meditation training consisted of 14 guided sessions each lasting 45 min over a time period of seven weeks. All sessions were held by the same instructor with over 15 years of yoga experience and a completed 4000 -h certification as a yoga teacher. Participants were instructed in elements of breathing (*pranayama*) and retraction of the senses (*pratyahara*). The students learned, for example, to blend out environment stimuli and rather focus on the own body and to concentrate the mind (*dharana*), which are considered to be preliminary stages of meditation (*dhyana*). The used techniques are consistent with FAM rather than open monitoring meditation. A detailed description of the meditation sessions and practices can be found in the appendix, table A1.

Study participants were advised to perform daily home practice for 15 min in week 1–4, for 20 min in week 5–8 and for 30 min from week 9 to the 2nd MRI appointment using FAM as thought in the formal sessions. The visualization of the meditation style was supported by a CD and an app created for this study.

2.3. Study questionnaires

Health-related quality of life was measured using the short form health survey (SF-36) and the German version of the State-Trait Anxiety Inventory (STADI). The SF-36 comprises eight domains including vitality, physical functioning, and bodily pain, general health perceptions, and physical, emotional and social role functioning, as well as mental health. Each scale score has a range from 0 to 100. High scores indicate a higher quality of life [23].

The STADI is a 40-item questionnaire based on a self-reported basis. This psychological inventory measures the current state of anxiety (S-anxiety) including the state of agitation, apprehension, euthymia and dysthymia, as well as trait-anxiety (T-anxiety) referring to the relatively stable aspects of anxiety as a personal characteristic, general states of calmness confidence and security [24]. The responses were given on a 4-point Likert-type scale for S-anxiety (1, not at all; 4, very much so) and for T-anxiety (1, almost never; 4, almost always) ranging from scale values 20–80. The questionnaires were filled out at baseline and follow-up time-point by the participants.

2.4. MRI acquisition

All participants underwent a predefined, standardized protocol utilizing a Siemens Skyra scanner with a field-strength of 3 T (Erlangen, Germany) at the Medical University of Innsbruck, Austria. The parameters for coronal T1-weighted 3D MPRAGE were as follows: repetition time (TR) 1800 ms; echo time (TE) 2.22 ms; flip angle 9°; in-plane field of view 256 × 192 mm; slice thickness 1 mm; 192 contiguous coronal slices; voxel resolution 1 1 1 mm. DWI data were acquired using spin-echo echo-planar imaging with following settings: echo time/repetition time = 92/9600 ms; bandwidth =1596 Hz/pixel; matrix size 128 × 128; 72 axial slices; voxel size 2 2 2 mm, 20 diffusion gradient directions, b-value of 1000 mm^2/s and one reference image with b = 0. These sequences were assessed by experienced neuroradiologists to exclude abnormal subclinical findings such as large confluent white matter lesions or infarctions.

2.5. Voxel-based morphometry

Whole brain analysis was conducted using an automated processing algorithm implemented in the Computational Anatomy Toolbox (CAT12; Structural Brain Mapping group, University of Jena, Germany) within SPM12 (Statistical Parametric Mapping, Institute of Neurology, London, UK) while running MATLAB 9.5 (R2018b; MathWorks, Natick, MA, USA). All high-resolution T1-weighted were bias-field corrected, skull-stripped, aligned to a Montreal Neurological Institute standard space (MNI-152 template) and segmented as gray matter, white matter, and cerebrospinal fluid [25]. Further, images were spatially normalized using the DARTEL algorithm [26]. To achieve accurate spatial normalization for DWI data, previously co-registered T1-weighted images were normalized onto the T1 template in Montreal Neurological Institute MNI space, and the resulting transformation parameters were applied to the participant's corresponding FA images. Spatially normalized parametric images were smoothed with a Gaussian kernel of 4 × 4 × 4 mm (FWHM) for T1-weighted and 8 × 8 × 8 mm for FA sequences. A masking threshold of 10 % was applied to reduce signal noise. MRI data were visually inspected for obvious artifacts arising from motion or instrumental failure or misalignments of brain structures.

2.6. Statistical analysis

Statistical analyses were carried out using the statistical software package SPSS version 24 (SPSS Inc., Chicago, IL, USA). Gaussian distribution was confirmed by visual analysis of the Q-Q plots and the Kolmogorov-Smirnov test. Group differences of normally distributed data were analyzed by parametric tests. A paired *t*-test was performed to assess in-between group differences of the SF-36 and the STADI questionnaire from pre to the post meditation training. The Benjamini and Hochberg false discovery rate (FDR) was used for multiple comparisons correction to control the false positive rate at 5%.

For voxel-based analysis of the whole brain, a general linear model was set up to compare longitudinal data from the baseline to the follow-up time-point using a flexible factorial design implemented in SPM12. Total intracranial volume, age and whole meditation time per week, defined as the sum of meditation classes and additional home practice in minutes, were entered as covariates to reduce related variance. Multiple linear regression analysis was used to reveal associations between GM alterations and significantly changed behavioral measures from pre to post meditation training. Results were corrected for multiple comparisons via the FDR at $P < 0.05$ level and the height-threshold was set to $P = 0.001$. For exploratory analysis, the averaged GM concentration of previously predetermined and frequently altered brain areas in meditation [9] was extracted for each individual at each time-point using standard settings for ROI extraction in the CAT12 toolbox. Raw values of extracted regions were transferred to SPSS for linear regression analysis.

3. Results

3.1. Clinical characteristics and mindfulness improvements

All participants completed the 14 guided meditation sessions resulting in a total of 10.5 h. The participants reported additional meditation at home practice in the same meditation style as thought in the formal sessions with an average duration of 24 min (range: 15 − 45 min) per day. Longitudinal analysis of the questionnaires revealed significant improvements for excitement ($P = 0.012$), concern ($P = 0.012$) and anxiety ($P = 0.004$) as well as psychological well-being ($P = 0.004$). Improved scores of the STADI questionnaire are presented in Table 1 and Fig. 1.

3.2. Longitudinal gray matter changes

Within-group comparison of the 27 meditation participants showed increased GM volumes at the follow-up compared to the baseline time-point in clusters of the anterior insula ($P = 0.001$), the inferior frontal gyrus ($P = 0.001$), the caudate nucleus with adjacent regions of the putamen ($P = 0.002$) and the superior frontal gyrus ($P = 0.003$) in each case bi-hemispheric as well as the middle spreading to the superior temporal gyrus ($P < 0.001$) and the cerebellum ($P = 0.004$) on the right side. Significant GM decreases were revealed in the inferior parietal lobule as well as the superior and middle temporal gyrus ($P < 0.001$) and the inferior frontal gyrus ($P = 0.001$) on both sides, as well as in the mPFC ($P < 0.001$) and the parahippocampal gyrus spreading to the fusiform gyrus ($P = 0.001$) on the right side. Additionally, GM decreases were found in the PCC at height-thresholds set to $P < 0.01$ ($P < 0.001$). No significant sex differences were found at height-thresholds set to $P < 0.01$ (Table 2, Fig. 2).

3.3. Longitudinal diffusion-weighted imaging analysis

Longitudinal analysis comparing the baseline to the follow-up time-point revealed increased FA values in the right basal ganglia including the right hippocampus spreading to the fusiform gyrus ($P = 0.041$) and the basal ganglia ($P = 0.012$) extending to the supraventricular white matter ($P = 0.01$) (Table 2, Fig. 3).

Table 1
Raw scores of the state-trait-anxiety-inventory at baseline and follow-up time-point.

	Baseline		Follow-up		P-values	
	State	Trait	State	Trait	State	Trait
Excitement	7.6 (2.6)	9.2 (3.2)	6 (1.7)	8.3 (2.7)	**0.012***	> 0.05
Concern	8 (2.8)	8 (2.5)	6.5 (1.6)	7.8 (2.4)	**0.012***	> 0.05
Euthymia	15.5 (3.5)	16.4 (2.1)	14.8 (3.5)	16.3 (2.4)	> 0.05	> 0.05
Dysthymia	5.6 (1.6)	7 (2)	5.3 (1.1)	6.2 (2.1)	> 0.05	> 0.05
Anxiety	15.5 (4.8)	16.8 (4.8)	12.6 (2.6)	16.1 (4)	**0.004***	> 0.05
Depression	14.7 (4)	14.8 (3.3)	15.3 (3.5)	14.9 (3.5)	> 0.05	> 0.05
Global-Score	30.4 (8.3)	31.2 (6.9)	27.1 (3.4)	30.5 (5.9)	> 0.05	> 0.05

Raw values of the state-trait-anxiety-inventory are represented as mean (± 1 standard deviation). The statistical tests are corrected for multiple comparisons (Holm-Sidak) in 5% significance level. *Statistically significant, $P < 0.05$.

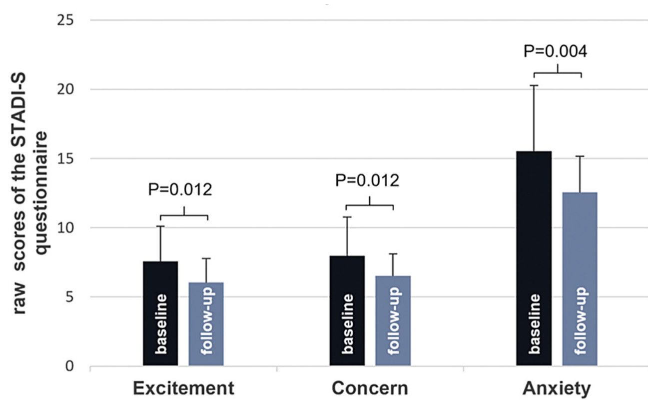

Fig. 1. Significant improvements assessed by the STADI-S questionnaire from baseline to follow-up time-point. Data are presented as mean and standard deviation.

3.4. Correlations between gray matter and behavioral improvements

Regression analysis revealed significant associations between STADI-S anxiety decreases and voxel clusters of the right mid cingulate (MCC) and PCC (P < 0.001) and the left mPFC (P < 0.001), as well as the right mPFC (P = 0.014) at height-thresholds set to 0.01 (Table 3, Fig. 4, for results in predefined regions see appendix, table A2).

4. Discussion

In this prospective longitudinal study, we demonstrated structural brain changes in a cohort of 27 meditation naïve participants following a 7-week focused attention meditation-program. The major findings comprised (i) GM increases in the insula, the caudate nucleus and frontal cortices bilaterally; (ii) GM decreases in extended parietotemporal regions bilaterally, the right mPFC and the parahippocampal gyrus; and (iii) FA increases of the right hippocampus and basal ganglia extending to the periventricular white matter. Participants reported significant lower levels of anxiety and increased levels of psychological well-being after meditation training.

Striking findings of the present study were increased GM volumes in the caudate nucleus and the anterior insula spreading to the inferior frontal lobe bilaterally. These results are consistent with previous cross-sectional and longitudinal studies which analyzed effects of Sahaja yoga meditation training and consistently found volume increases in fronto-insular cortices [15,27]. Fronto-insular cortices were revealed to be activated during meditative states [7,28,29] and to play a critical role in switching and suppressing central-executive and DMN activity [30]. Further, neuroanatomical enhancements predominantly of the insula

Table 2
Statistical parametric mapping findings showing significant gray matter and fractional anisotropy alterations in meditation participants after 7 weeks focused attention meditation training compared to the initial time-point.

	Cluster size (number of significant voxels)	MNI coordinates			*t* value	*P* value corrected at peak level (FDR)*	Height-threshold
		X	Y	Z			
Significant gray matter increases in the 27 meditation participants from baseline to follow-up time-point							
Right-hemispheric							
Anterior Insula	117	30	29	−5	9.91	< 0.001	0.001
Inferior frontal gyrus, Pars opercularis, BA 44	148	48	14	14	7.50	0.001	
Middle spreading to the superior temporal gyrus	159	47	−17	−12	8.01	< 0.001	
Caudate nucleus	121	12	21	−5	6.54	0.002	
Superior frontal gyrus, BA 10	109	12	68	12	5.94	0.003	
Right anterior cerebellum	108	32	−44	−41	5.77	0.004	
Left-hemispheric							
Anterior insula spreading to the inferior frontal gyrus, Pars orbitalis	176	−29	26	−6	6.76	0.001	0.001
Inferior frontal gyrus, Pars opercularis	127	−48	11	11	5.65	0.005	
Caudate nucleus	153	−8	20	−5	7.3	0.001	
Putamen		−9	11	−11	4.93	0.011	
Significant gray matter decreases in the 27 meditation participants from baseline to follow-up time-point							
Right-hemispheric							
Inferior parietal lobule and superior and middle temporal gyrus	2140	66	−35	29	10.13	< 0.001	0.001
		69	−35	14	9.38		
Inferior frontal gyrus, Pars opercularis and triangularis, BA 44, BA 45, and precentral gyrus	123	60	15	14	6.08	0.001	
	97	59	26	15	5.21	0.002	
		42	6	27	4.64	0.006	
Medial prefrontal cortex (mPFC)	211	9	35	−5	6.92	< 0.001	
Parahippocampal spreading to the fusiform gyrus, BA 35	165	35	−23	−24	6.54	0.001	
	111	24	−12	−30	5.84		
Mid and posterior cingulate	812	0	−33	41	4.62	< 0.001	0.01
Left-hemispheric							
Inferior parietal lobule, precentral gyrus, BA 40	1080	−65	−12	27	8.54	< 0.001	0.001
		−62	−44	38	7.57		
Middle temporal gyrus, BA 21	171	−68	−41	−5	8	< 0.001	
Inferior frontal gyrus, Pars triangularis and orbitalis, BA 45, BA 47	134	−56	21	14	6.84	< 0.001	
	119	−29	32	−12	5.8	0.001	
Significant fractional anisotropy increases in the 27 meditation participants from baseline to follow-up							
Right periventricular white matter	430	28	−20	36	4.92	0.001	0.01
Right hippocampus	216	38	−26	−8	4.86	0.016	
Right thalamus extending to the stria terminalis	563	20	−6	14	4.69	0.012	

MNI, Montreal Neurological Institute coordinates; *fractional anisotropy results are FWE-corrected at P < 0.05 with the height-threshold set to P < 0.01.

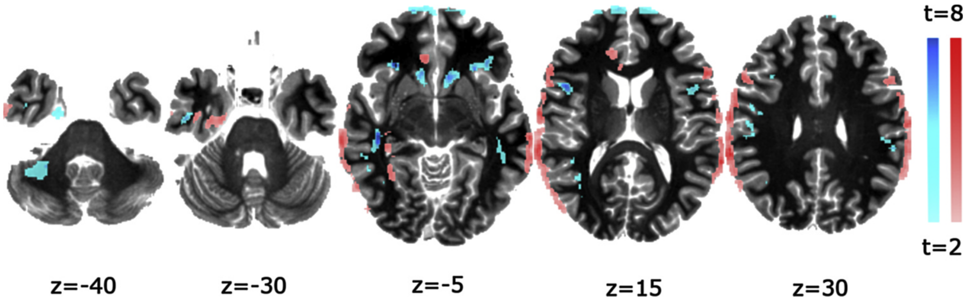

Fig. 2. Statistical parametric mapping axial maximum intensity projection maps rendered onto a stereo-tactically normalized MRI scan showing areas of significant gray matter density increases (red color) and decreases (blue color) in the 27 participants after 7 weeks focused attention meditation training compared to the initial time-point. The resulting statistical maps are FDR-corrected at $P < 0.05$ with a height-threshold set to $P < 0.001$. The number at the bottom of each MRI scan corresponds to the z coordinate in Montreal Neurological Institute space.

were related to the amount of yoga experience and a higher cold pain tolerance [31]. Converging evidence suggests that the insula is especially involved in techniques focusing on body awareness, including attention to body position and respiration [10,19,32,33]. Therefore, we propose that cortical reorganization processes in fronto-insular regions are associated to practiced FAM and promote sustained attention, self-control and self-awareness [27,34]. Further, these findings are consistent with previous longitudinal studies that revealed structural plasticity in fronto-insular cortices and associated beneficial effects on general well-being after Sahaja yoga meditation training [15] as well as several improved psychological indices including concern and state anxiety after a mindfulness-based stress reduction program [14]. Fronto-insular GM increases as observed in our participants may be the result of their increased awareness of bodily sensations. Our findings also add evidence to a previous cross-sectional study which reported increased activity in the anterior insula and the dorsolateral prefrontal cortex as well as structural differences in the caudate nucleus when comparing meditators to non-meditators [35]. Meditation induced changes in the anatomy of the caudate nucleus may be relevant, as the caudate nucleus is known to play an important role for the habitual direction of attention and behavior [36].

In our opinion the most interesting and novel findings of the present study were the relative patterns of GM increases accompanied by significant decreases. Interestingly, the meditation cohort revealed reduced GM density in several regions including the right mPFC, the lateral parietal and temporal cortex, and the right parahippocampal gyrus. Recent fMRI studies showed that activity in brain regions of the DMN including the anterior cingulate cortex, fusiform gyrus, middle temporal gyrus, and precuneus is consistently decreased during meditation compared to an active task [37,38]. Reduced activity may promote a usage-dependent selective elimination of synapses [39] leading to GM reductions in the mPFC, precuneus and right parahippocampal gyrus. In previous studies initial training-induced GM increases were followed by decreases suggesting a non-linearity of training induced neuroplasticity [40,41], as well as an affectability by training length and intensity [39]. Further, previous findings demonstrated that lower cortical thickness might be accompanied by increased cognitive functions after training [39,42]. In this context, we assume that all regions showing structural changes are involved in meditation training, and that increases may be followed by decreases especially in regions related to emotional regulation and self-referential processing. In accordance to this, a recent cross-sectional study revealed reductions of cortical thickness in extensive parietal areas when comparing meditators to healthy controls, suggesting that decreased GM in these regions may be associated with enhanced cognitive functions such as attention and self-perception [19]. The mPFC was identified as a region showing structural differences in meditation novices even after having undergone brief (5–60 hour) training [43]. Meditation associated plasticity in this region was reported in several studies for both, structural changes and enhanced functional connectivity [19,44]. In contrast to previous studies [19,45], the present study cohort showed GM decreases instead of increases in the mPFC and no significant structural effects in the PCC which was demonstrated to be a debated region showing inconsistent findings [16,19]. Therefore, these patterns may be dependent of meditation style as well as training length and intensity. In accordance to this, a stronger rightward asymmetry in the mPFC was negatively associated with the number of meditation practice years [46].

Considerable evidence from functional neuroimaging analyses suggests that neurons of altered brain regions are involved in numerous clinical disorders and behavioral functions. Several studies have documented the positive impact of meditation techniques on anxiety and depression [1,2,16], and sustained attention [3,4]. Increased parahippocampal volume was associated with neurotic trait anxiety [47] and parahippocampal hyperactivity was found in individuals with social phobia during conditions of social threat [48]. The mPFC and the PCC are part of the DMN and known to play an important role in the pathophysiology of anxiety disorder [49]. Morphological changes in these regions might contribute to some behavioral enhancements including improved anxiety levels and psychological well-being. In addition, we found significant relationships between improvements in behavioral measures, especially state anxiety, and GM volume predominantly in the PCC, the precuneus and supramarginal gyrus. The cingulate cortex is a highly metabolic active and interconnected region, which receives a large part of its afferent axons form the thalamus and sends projections to the posterior areas [50]. The PCC receives body-orientation inputs from the mPFC, further combines it with autobiographical and contextual information, and sends it to the precuneus to create a final representation of the person in a spatial context [51].

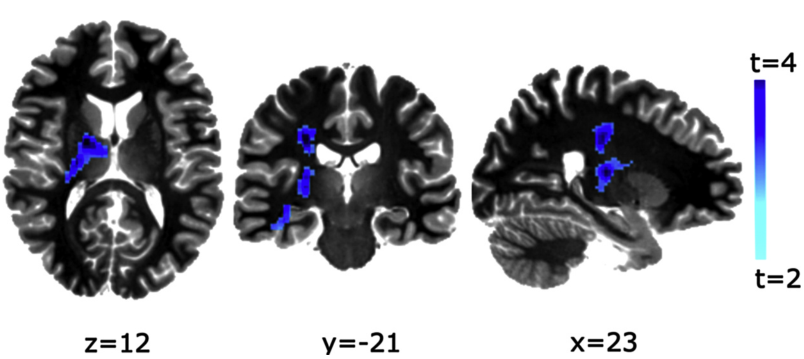

Fig. 3. Statistical parametric mapping axial maximum intensity projection maps rendered onto a stereo-tactically normalized MRI scan, showing areas of significant fractional anisotropy increases in the 27 individuals after focused attention meditation training compared to the initial time-point (color code, yellow to orange). The resulting statistical maps are FWE-corrected at $P < 0.05$ with the height-threshold set to $P < 0.01$. The number at the bottom of each MRI scan corresponds to the x, y and z coordinates in Montreal Neurological Institute space.

Table 3
Statistical parametric mapping findings showing significant associations between gray matter and improved behavioral measures, i.e. state anxiety, in meditation participants after 7 weeks focused attention meditation training compared to the initial time-point.

	Cluster size (number of significant voxels)	MNI coordinates			*t* value	*P* value corrected at FWE-corrected cluster level	Height-threshold
		X	Y	Z			
Significant associations between gray matter and reduced state anxiety in the 27 meditation participants from baseline to follow-up time-point							
Right-hemispheric							
Mid and posterior cingulate	538	2	−41	36	5.86	< 0.001	0.001
		12	−42	38	4.81		
		9	−51	18	3.79		
Posterior cingulate	197	17	−56	8	3.65	0.017	
Anterior cingulate, mPFC	721	3	45	−5	4.27	0.014	0.01
		6	36	−5	3.93		
Left-hemispheric							
Anterior cingulate, mPFC	197	−8	41	−6	5.79	< 0.001	0.001
		−6	32	−17	5.13		
Posterior cingulate	515	−12	−60	6	3.77	0.091	0.01

MNI, Montreal Neurological Institute coordinates.

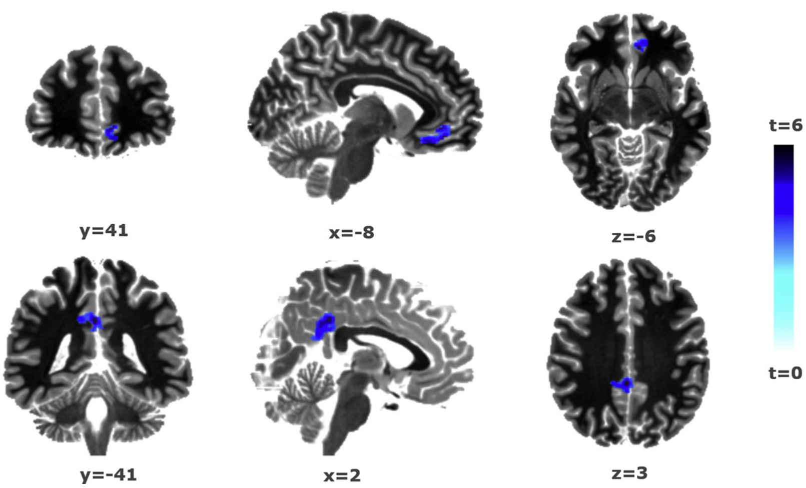

Fig. 4. Statistical parametric mapping axial maximum intensity projection maps rendered onto a stereo-tactically normalized MRI scan, showing areas of significant associations between gray matter density and reduced state anxiety in the 27 participants after focused attention meditation training compared to the initial time-point (color code, yellow to red). The resulting statistical maps are FWE-corrected at $P < 0.05$ with the height-threshold set to $P < 0.001$. The number at the bottom of each MRI scan corresponds to the x, y and z coordinates in Montreal Neurological Institute space.

Volumetric alterations in these regions may reflect alterations in network processing changing the way of reflecting one's own body. Referring to this, individuals with high trait anxiety showed a decreased DMN functional connectivity between the right mPFC and PCC [52].

Our results support the theory of dynamic neuronal adaption of fiber tracts in the central nervous system induced by the accommodation of new information and experiences as a consequence of FAM. FA increases of the thalamus and adjacent structures may be interpreted as improved connections leading to a higher capacity of information flow and might be relevant since the thalamus is considered to play a role in relaying sensory information to the cerebral cortex and to be implicated in emotional processing [19]. Previous studies revealed significant FA changes in the corticospinal tract, the uncinate fasciculus and parts of the superior longitudinal fascicle as well as an increased WM integrity in the corpus callosum in experienced meditators [17,18,53]. Tang et al. demonstrated that alterations in axonal integrity can occur very rapidly even after an 11 -h integrative body-mind training showing increased FA in the corona radiata connecting the cingulate cortex [32].

4.1. Limitations

While highlighting potential effects of meditation on neuronal plasticity, it is noteworthy that GM alterations in voxel-based morphometry can be induced by several factors including neural or glial cell genesis, dendritic arborization and axonal remodeling, or even changes in the blood flow or interstitial fluid [54]. Structural plasticity is believed to rely on a cascade of molecular processes that increase myelin and axonal connectivity resulting in enhanced brain functions [55]. Since the primary objective of our study was to identify and relate FAM to structural brain reorganization processes, we recruited meditation naïve people from the general population with an age range from 30 to 55 years at baseline and observed behavioral and brain structural measures longitudinally following meditation training. Whether these results can be allocated for all age groups needs to be investigated in future studies. However, the interpretation whether changes in behavioral measures were driven by meditation training or, for instance, by the group experience remains unclear. Further, we cannot completely rule out that specific effects on brain structure are contributed by additional factors including socializing and relaxation. Despite our best efforts, some confounding factors such as scanner drift are inevitable. While bilaterally symmetric changes in a set of regions were shown in previous cross-sectional studies, we observed right-sided unilateral patterns in the FA results. This might be explainable by a too short period of meditation training. Follow-up studies on the same participants with home-based meditation might bring further insights on both conflicting interpretations discussed.

4.2. Conclusions

This is one of few longitudinal studies that investigated cortical reorganization as indexed by brain structure and axonal integrity in a cohort of meditation naïve participants before and after FAM meditation training. We were able to partially confirm and extend previous findings of short-term meditation training induced brain changes in the adult human brain. Interestingly, the present analysis revealed more regions of structural change than most other prior studies discussing structural alterations from meditation. These results further suggest that dynamic alterations in brain structure can occur very rapidly within a time range of few weeks. We interpret our results that FAM induces a broad range of cortical reorganization processes, which are different to other meditation techniques and associated with potential positive regulatory functions. Further studies with larger cohorts and longer training periods as well as more advanced neuropsychological testing are warranted to link morphological changes to cognitive and behavioral functioning and to see if induced changes persist in the absence of continued meditation practice. The broad impact on neuronal organization processes caused by FAM practice may in turn reflect other outcomes related to health and well-being.

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Declarations of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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